

# Influence of Departures from LTE on Oxygen Abundance Determination

T. M. Sitnova<sup>\*1,2</sup> L. I. Mashonkina<sup>1</sup>, T. A. Ryabchikova<sup>1</sup>

<sup>1</sup> *Institut of Astronomy of RAS, Moscow, Russia*

<sup>2</sup> *Moscow M.V. Lomonosov State University, Moscow, 119991 Russia*

## Abstract

We have performed non-LTE calculations for O I with the classical plane-parallel (1D) model atmospheres for a set of stellar parameters corresponding to stars of spectral types from A to K. The multilevel model atom produced by Przybilla et al. (2000) was updated using the best theoretical and experimental atomic data available so far. Non-LTE leads to strengthening the O I lines, and the difference between the non-LTE and LTE abundances (non-LTE correction) is negative. The departures from LTE grow toward higher effective temperature and lower surface gravity. In the entire temperature range and  $\log g = 4$ , the non-LTE correction does not exceed 0.05 dex in absolute value for lines of O I in the visible spectral range. The non-LTE corrections are significantly larger for the infrared O I 7771-5 Å lines and reach -1.9 dex in the model atmosphere with  $T_{\text{eff}} = 10000$  K and  $\log g = 2$ . To differentiate the effects of inelastic collisions with electrons and neutral hydrogen atoms on the statistical equilibrium (SE) of O I, we derived the oxygen abundance for the three well studied A-type stars Vega, Sirius, and HD 32115. For each star, non-LTE leads to smaller difference between the infrared and visible lines. For example, for Vega, this difference reduces from 1.17 dex in LTE down to 0.14 dex when ignoring LTE. To remove the difference between the infrared and visible lines completely, one needs to reduce the used electron-impact excitation rates by Barklem (2007) by a factor of 4. A common value for the scaling factor was obtained for each A-type star. In the case of Procyon and the Sun, inelastic collisions with H I affect the SE of O I, and agreement between the abundances from different lines is achieved when using the Drawin's formalism to compute collisional rates. The solar mean oxygen abundance from the O I 6300, 6158, 7771-5, and 8446 Å lines is  $\log \varepsilon = 8.74 \pm 0.05$ , when using the MAFAGS-OS solar model atmosphere and  $\log \varepsilon = 8.78 \pm 0.03$ , when applying the 3D corrections taken from the literature.

**Keywords:** stellar atmospheres, spectral line formation under nonequilibrium conditions, solar and stellar oxygen abundance.

---

\*sitnova@inasan.ru

# 1 Introduction

Oxygen abundances of cool stars with different metallicities are important for understanding the galactic chemical evolution. The O I 7771-Å line is observed for stars in a wide range of spectral types from B to K, and this is the only set of atomic oxygen lines that is observed in the spectra of metal-poor stars. Previously, many authors have shown that different O I lines give different abundances, with the infrared (IR) O I 7771-5 Å triplet exhibiting a systematically higher abundance, occasionally by an order of magnitude higher than the remaining lines do. The reason is that the IR O I lines are formed under conditions far from local thermodynamic equilibrium (LTE). The oxygen abundance was first determined by abandoning LTE (within the so-called non-LTE approach) by Kodaira and Tanaka (1972) and Johnson (1974) for stars and by Shchukina (1987) for the Sun. Subsequently, more complex model atoms for O I were constructed by Kiselman (1991), Carlsson and Judge (1993), Takeda (1992), Paunzen et al. (1999), Reetz (1999), Mishenina et al. (2000), and Przybilla et al. (2000). Allowance for non-LTE effects leads to a strengthening of lines and, consequently, to a decrease in the abundance derived from these lines. For A-type main-sequence stars and F supergiants, even if the departures from LTE are taken into account, the IR O I lines still give a systematically higher abundance (by 0.25 dex for Vega; Przybilla et al. 2000) than do the visible lines, for which the departures from LTE are small ( $< 0.05$  dex in absolute value).

Solar abundance of oxygen is a key parameter for the studies of solar physics. Having considered atomic and molecular lines in the solar spectrum, Asplund et al. (2004) achieved agreement between the abundances from different lines using a three-dimensional (3D) model atmosphere based on hydrodynamic calculations. In Asplund et al. (2004), the mean abundance from atomic and molecular lines is  $\log \varepsilon = 8.66 \pm 0.05$ ; subsequently, these authors obtained  $\log \varepsilon = 8.69$  by the same method (Asplund et al. 2009). Here,  $\log \varepsilon = \log(n_{\text{elem}}/n_{\text{H}})+12$ . This value turned out to be lower than  $\log \varepsilon = 8.93 \pm 0.04$  obtained previously by Anders and Grevesse (1989) from OH molecular lines using the semi-empirical model atmosphere of Holweger and Mueller 1974 (HM74). It should be noted that solar models constructed with the chemical composition from Anders and Grevesse (1989) described well the sound speed and density profiles inferred from helioseismological observations. A downward revision of the oxygen abundance by 0.27 dex led to a discrepancy between the theory and observations up to  $15 \sigma$  (Bahcall and Serenelli 2005). Delahaye and Pinsonneault (2006) showed that the depth of the convection zone and the helium abundance deduced from observations allow a lower limit to be set on the surface oxygen abundance,  $\log \varepsilon = 8.86 \pm 0.05$ . This value is larger than that from Asplund et al. (2009) by 0.17 dex (more than  $3\sigma$ ) and that from Caffau et al. (2008) by 0.10 dex ( $2\sigma$ ). The authors suggested that such discrepancies could be due to imperfections of modeling the stellar atmospheres and line formation. In their next paper, Pinsonneault and Delahaye (2009) analyzed the errors in analyzing the solar oxygen lines and concluded that the atmospheric abundance error could reach 0.08 dex. This is greater than that given by Asplund et al. (2009, 0.05 dex) and is close to the error in Caffau et al. (2008, 0.07 dex).

Why do the abundances derived by Asplund et al. (2004, 2009) and Anders and Grevesse (1989) differ? The molecular lines are known to be very sensitive to the temperature distribution in a model atmosphere. In the surface layers where the lines originate, the temperature in 3D

model atmospheres is lower than that in classical 1D models, MARCS (Gustafsson et al. 2008) and HM74. Therefore, the molecular lines computed with a 3D model are stronger, while the abundances inferred from them are lower.

For the Sun and cool stars, the non-LTE abundance derived from atomic lines can be inaccurate due to the uncertainty in calculating poorly known collisions with H I atoms. Accurate quantum-mechanical calculations of collisions with hydrogen atoms are available only for a few atoms: for Li I (Belyaev and Barklem 2003), Na I (Belyaev et al. 1999, 2010; Barklem et al. 2010), and Mg I (Barklem et al. 2012). Since there are no accurate calculations and laboratory measurements of the corresponding cross sections, these are calculated from the formula derived by Steenbock and Holweger (1984) using the formalism of Drawin (1968, 1969). The authors themselves estimate the accuracy of the formula to be one order of magnitude. A scaling factor ( $S_H$ ) that can be found by reconciling the abundances from lines with strong and weak departures from LTE is usually introduced in this formula. For example, for Na I (Allende Prieto et al. 2004), Fe I-Fe II (Mashonkina et al. 2011), and Ca I-Ca II (Mashonkina et al. 2007) atoms, these scaling factors are 0, 0.1, and 0.1, respectively. For oxygen, Allende Prieto et al. (2004) and Pereira et al. (2009) obtained  $S_H = 1$  by investigating the changes of the O I line profiles in different regions of the solar disk; Takeda (1995) obtained the same result from O I lines in the solar flux spectrum. For the Sun and cool stars, agreement between the abundances determined from different O I lines can be achieved by choosing a scaling factor. Caffau et al. (2008) performed non-LTE calculations for O I with  $S_H = 0, 1/3$ , and 1. The higher the efficiency of the collisions with hydrogen atoms, the smaller the departures from LTE and the higher the abundance. For example, for the IR O I 7771 Å line, the abundance inferred with  $S_H = 1$  is higher than that with  $S_H = 0$  by 0.12 dex. Asplund et al. (2009) disregarded the hydrogen collisions ( $S_H = 0$ ). Note that when using the same methods (non-LTE,  $S_H = 0$ , 3D model atmospheres) and common atomic lines, Caffau et al. (2008) and Asplund et al. (2004) give  $\log \varepsilon = 8.73$  and  $\log \varepsilon = 8.64$ , respectively. At such a difference between different authors (0.09 dex), the solar oxygen abundance cannot be considered a well-determined quantity. The accuracy of non-LTE calculations depends not only on the reliability of the data for collisions with hydrogen atoms but also on the data for collisions with electrons. To improve the accuracy of non-LTE results, Barklem (2007) calculated new cross sections for the excitation of O I transitions under collisions with electrons. These data were used by Fabbian et al. (2009) to determine the abundance and to analyze the departures from LTE for IR lines in cool metal-poor stars with an effective temperature  $T_{\text{eff}} = 4500 - 6500$  K. It is well known (see, e.g., Sneden et al. 1979) that in LTE the oxygen overabundance with respect to iron increases with decreasing metallicity, so that  $[\text{O}/\text{Fe}]$  reaches 0.5 dex already at metallicity  $[\text{Fe}/\text{H}] = -1$ . (Here, the universally accepted designation  $[\text{X}/\text{Y}] = \log(n_X/n_Y)_* - \log(n_X/n_Y)_\odot$  is used.) The problem of oxygen overabundances was considered using a non-LTE approach by Abia and Rebolo (1989), Mishenina et al. (2000), and Nissen et al. (2002). Allowance for the departures from LTE does not eliminate the  $[\text{O}/\text{Fe}]$  overabundance, but it is reduced. Nissen et al. (2002) disregarded the hydrogen collisions and obtained a linear growth of  $[\text{O}/\text{Fe}]$  from 0 to 0.3 at  $0 > [\text{Fe}/\text{H}] > -1$ , which was replaced by an almost constant ratio at  $-1 > [\text{Fe}/\text{H}] > -2.7$ . The same result was obtained by Fabbian et al. (2009) with the data from Barklem (2007), but with allowance made for the hydrogen collisions with  $S_H = 1$ . In this case, the introduction

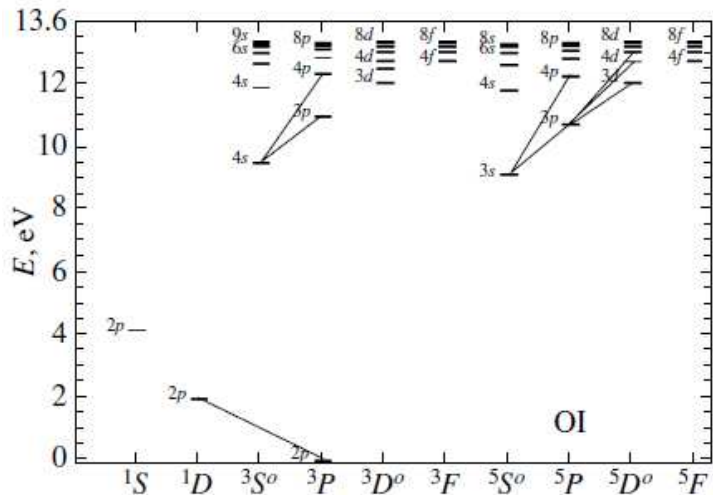


Figure 1: O I model atom. The straight lines correspond to the transitions in which the lines under study are formed.

of hydrogen collisions compensates for the decrease in the rate coefficient for collisions with electrons in Barklem (2007) in comparison with the previous data. With Barklem's new data and without any hydrogen collisions, the non-LTE effects increase. Thus,  $\Delta_{non-LTE} = -1.2$  dex at  $[\text{Fe}/\text{H}] = -3.5$  ( $T_{\text{eff}} = 6500$  K,  $\log g = 4$ ) and the  $[\text{O}/\text{Fe}]$  ratio decreases with decreasing metallicity (Fabbian et al. 2009), which cannot be explained by the existing nucleosynthesis models.

The goal of our paper is to obtain a reliable method of determining the oxygen abundance for stars of spectral types from A to K from different O I lines. First, we checked how using the new data from Barklem (2007) affects the oxygen abundance determination for hot stars with  $T_{\text{eff}} > 7000$  K, for which the statistical equilibrium of O I does not depend on collisions with neutral hydrogen atoms. We analyzed the spectra of four stars with reliably determined parameters. Then we estimated  $S_{\text{H}}$  by analyzing the O I lines for the Sun and Procyon. We performed an independent analysis of the solar O I lines using the most accurate available atomic data and modeling methods to understand the possible causes of the uncertainties in determining the solar oxygen abundance and to try to refine its value. We describe the model atom and the mechanism of departures from LTE in Section 2, the methods and codes used in Section 3, and the observations and stellar parameters in Section 4. We present the results for hot stars in Section 5 and for the Sun and Procyon in Section 6. We also calculated the non-LTE corrections for a grid of model atmospheres; these are given in Section 7.

## 2 The model atom and statistical equilibrium of oxygen

We used the model atom from Przybilla et al. (2000). It includes 51 levels of O I and the O II ground state (Fig. 1). The oxygen levels belong to the singlet, triplet, and quintet terms. The

maximum principal quantum number in this model is  $n = 10$ . The model atom accounts for the radiative and collisional processes in bound-free and bound-bound transitions. The atomic data used are described in detail in Przybilla et al. (2000). Przybilla et al. (2000) point out that the uncertainty in the data for collisions with electrons makes the most significant contribution to the uncertainty in final results of non-LTE calculations for hot stars. They estimated the accuracy of the atomic data to be 10% for radiative transitions and 50% for collisional ones.

To improve the accuracy of non-LTE calculations, Barklem (2007) calculated new cross sections for the excitation of O I transitions under collisions with electrons. In the model atom, we made changes for 153 transitions associated with the new theoretical calculations by Barklem (2007). In the model atom from Przybilla et al. (2000), the rate coefficients for these transitions were calculated using either the formula from Wooley and Allen (1948), or the formula from van Regemorter (1962), or the data from Bhatia and Kastner (1995). Table 1 compares the rate coefficients for several transitions at temperature  $T = 8750$  K and electron density  $n_e = 1.3 \cdot 10^{15} \text{ cm}^{-3}$  for the model atom from Przybilla et al. (2000) (the P00 column) and our updated model with the data from Barklem (2007) (the B07 column). The chosen parameters correspond to the atmosphere of Vega at depth  $\log(\tau_{5000}) = -1$ . As an example, we took several transitions with energies  $\Delta E_{ij} < 2$  eV, because a change in the rate coefficients with larger and smaller energy separations affects weakly the statistical equilibrium of O I. The rate coefficients increased by several orders of magnitude for some transitions and decreased for others. Most importantly, the new rate coefficients decreased for the transitions with the largest rate coefficients, which affect most strongly the statistical equilibrium of O I. A change in the data for the transitions from the ground level and the transitions between triplet and quintet levels does not affect the result, as was previously shown by Kislman (1991) and Carlsson and Judge (1993). The departures from LTE are commonly characterized by b-factors,  $b_i = n_{i\text{non-LTE}}/n_{i\text{LTE}}$ , where  $n_{i\text{non-LTE}}$  and  $n_{i\text{LTE}}$  are the populations of the  $i$ -th level in the non-equilibrium and equilibrium cases. Figure 2 shows the behavior of the b-factors for several levels in the atmospheres of Vega ( $T_{\text{eff}} = 9550$  K) and the Sun ( $T_{\text{eff}} = 5780$  K). The qualitative behavior of the b-factors in the atmosphere is similar; the only difference is that the departures from LTE for Vega are stronger due to the higher  $T_{\text{eff}}$  and lower  $\log g$ . Two types of processes compete between themselves in the stellar atmosphere: collisional ones, which tend to bring the system to equilibrium, and radiative ones, which hinder them. The collisional transition rates depend on local parameters of the medium, while the radiative ones depend on the mean intensities of radiation that are non-local quantities in the upper atmospheric layers, where the photon mean free path is large. Where the density is high, the rate of collisional processes is higher than that of radiative ones; the conditions are close to equilibrium ones. In deep layers ( $\log(\tau_{5000}) > 0$  for the Sun and  $\log(\tau_{5000}) > 1$  for Vega), the populations of all levels do not differ from the equilibrium ones. In the atmospheres of the Sun and Vega, most of the O I atoms are at levels of the main 2p configuration (the three lower levels in Fig. 1). Even for Vega, the ratio of the O I and O II ground level populations  $n_{\text{O I}}/n_{\text{O II}} > 10$  at depths  $\log(\tau_{5000}) < 0.3$ . Therefore, the populations of all three levels do not differ from the equilibrium one. The O I and O II ground levels are related by the charge exchange reaction  $\text{H}^+ + \text{O} \leftrightarrow \text{H} + \text{O}^+$ , because the O I and H I ionization potentials are closely spaced (13.62 and 13.60 eV, respectively). As a result, the O II level population follows the O I ground state population, and the b-factors

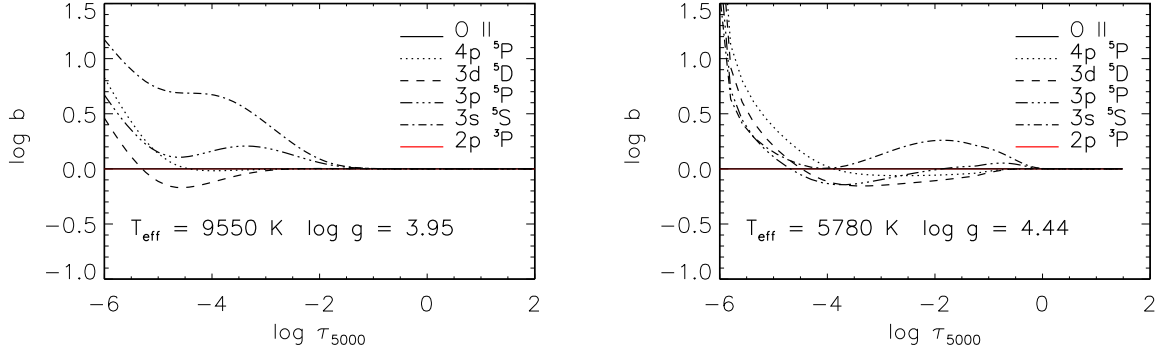


Figure 2: b-factors for oxygen levels in the atmospheres of Vega (left) and the Sun (right).

in the figure merge together. Spontaneous transitions from the highly excited levels tightly coupled with the O II ground state lead to overpopulation of the lower states. The  $3s\ ^3S^\circ$  and  $3s\ ^5S^\circ$  levels are overpopulated more than all other levels. To understand how the line profile changes under non-equilibrium conditions, one should take a look at the behavior of the b-factors for upper ( $b_j$ ) and lower ( $b_i$ ) levels at the line formation depth. The line profile is affected by the deviation of the source function ( $S_\nu$ ) from the Planck function ( $B_\nu$ ) and the change in opacity ( $\chi_\nu$ ) under non-equilibrium conditions. In the visible range, these quantities depend on the b-factors as follows:

$$S_\nu \sim B_\nu b_j / b_i, \quad \chi_\nu \sim b_i$$

For the strong IR O I 7771-5 Å (the  $3s\ ^5S^\circ - 3p\ ^5P$  transition) lines, whose core is formed at depth  $\log(\tau_{5000}) \simeq -2$ , departures from LTE are large due to overpopulation of lower-level and  $b_{3p\ ^5P} / b_{3s\ ^5S^\circ} < 1$  (Fig. 2), that leads to the strengthening of the lines. The visible (3947, 4368, 5330, 6155-9 Å) O I lines also strengthen. However, since they are weak and originate in deep layers, non-LTE effects do not lead to such a dramatic change of the line profiles. The forbidden 6300 Å line is immune to departures from LTE. It is formed in the  $2p\ ^3P - 2p\ ^1D^\circ$  transition, whose level populations do not differ from the equilibrium ones.

Table 1: Rate coefficients for collisional transitions in different model atoms for oxygen.

Transition	$C_{lu}, c^{-1}cm^{-3}$ (P00)	$C_{lu}, c^{-1}cm^{-3}$ (B07)
$2p\ ^3P^\circ - 2p\ ^1D^\circ$	6.794e5	2.357e4
$3s\ ^5S^\circ - 3s\ ^3S^\circ$	5.275e3	5.910e6
$3s\ ^5S^\circ - 3p\ ^5P$	1.041e7	7.611e6
$3s\ ^3S^\circ - 3p\ ^3P$	1.573e7	8.524e6
$3p\ ^5P - 3p\ ^3P$	1.255e6	1.743e6

### 3 The codes and methods

We calculated the equilibrium and non-equilibrium level populations using the DETAIL code developed by Butler and Giddings (1985) and based on the method of an accelerated  $\lambda$  – iteration. The opacity in continuum and lines (42 million lines for 90 elements) is taken into account. The output data from the DETAIL code (level populations) were then used to compute a synthetic spectrum by different codes. For stars with  $T_{\text{eff}} < 7500$  K, we applied the SIU (Spectrum Investigation Utility) code (Reetz 1999), which allows a synthetic spectrum to be computed in the equilibrium and non-equilibrium cases. For the remaining stars, we used the SYNTH3 code (O. Kochukhov), with which the LTE abundance can be calculated and the line equivalent widths can be measured. To derive the non-LTE abundances, we worked with the equivalent widths in the LINEC code (Sakhibullin 1983). The same code was used to calculate the non-LTE corrections for a grid of model atmospheres. A preliminary test shows that different codes give the same abundance within 0.02 dex.

### 4 Observations and stellar parameters

We used high-spectral-resolution observations whose characteristics are listed in Table 2. Table 3 gives the stellar parameters taken from the literature. For Procyon, the effective temperature and surface gravity were determined, respectively, by the method of IR fluxes and the astrometric method (Chiavassa et al. 2012). For Vega and Deneb, the effective temperatures and surface gravities were determined from the Balmer line wings and Mg I and Mg II lines (Przybilla et al. 2000; Schiller and Przybilla 2008). For HD 32115, the effective temperature and surface gravity were determined, respectively, from the  $H_\gamma$  line wings and the Mg I line wings taking into account the departures from LTE (Fossati et al. 2011). For Sirius, we took Kurucz’s model atmosphere (<http://kurucz.harvard.edu/stars/SIRIUS/ap04t9850g43k0he05y.dat>) computed with parameters close to those derived by Hill and Landstreet (1993). We decided to independently determine the microturbulence for Sirius, because the published values vary in a wide range between  $\xi_t = 1.7 \text{ km c}^{-1}$  (Hill and Landstreet 1993) and  $\xi_t = 2.2 \text{ km c}^{-1}$  (Landstreet 2011). The microturbulence is usually determined by the value at which the dependence of the elemental abundance derived from individual lines on equivalent widths vanishes. The most accurate value of this parameter is obtained when using lines with a wide range of observed equivalent widths, from several to 100-150 mÅ. In the spectrum of Sirius, the lines of ionized iron meet this criterion. To determine the microturbulence, we selected 27 Fe II lines with equivalent widths in the range from 9 to 170 m Å and with fairly reliable oscillator strengths. All lines were carefully checked for possible blending by comparison with a synthetic spectrum computed with a sample of lines from VALD (Kupka et al. 1999). For a more reliable determination of the microturbulence, we used two sets of oscillator strengths: theoretical calculations based on the method of orthogonal operators (Raassen and Uylings 1998) and a recent compilation by Melendez and Barbuy (2009). In Fig. 3, the iron abundance from individual lines is plotted against the equivalent width for  $\xi_t = 1.4, 1.7$ , and  $2.0 \text{ km c}^{-1}$ . For both sets of oscillator strengths, we obtained a consistent microturbulence,  $\xi_t = 1.7 - 1.8 \text{ km c}^{-1}$ , with an error of  $\pm 0.3 \text{ km c}^{-1}$ . Our result is in good agreement with  $\xi_t = 1.7 \text{ km c}^{-1}$  and  $\xi_t = 1.85 \text{ km c}^{-1}$  from

Hill and Landstreet (1993) and Qiu et al. (2001). The value of  $\xi_t = 2 \text{ km c}^{-1}$  used in some papers (Lemke 1990; Hui-Bon-Hoa et al. 1997; Landstreet 2011) probably results from the fact that small blends were disregarded when measuring the equivalent widths and determining the abundance from strong Fe II and Fe I lines.

We used classical 1D model atmospheres computed with the following codes: LLmodels (Shulyak et al. 2004) for HD 32115 and Vega, MAFAGSOS (Grupp et al. 2009) for the Sun and Procyon, ATLAS12 (R. Kurucz) for Sirius, and ATLAS9 (Kurucz 1994) for Deneb, and to calculate the non-LTE corrections for a grid of model atmospheres. Using different codes to compute model atmospheres is admissible, because our goal is to achieve agreement between the abundances from different lines for each star, not to compare the abundances for stars with one another.

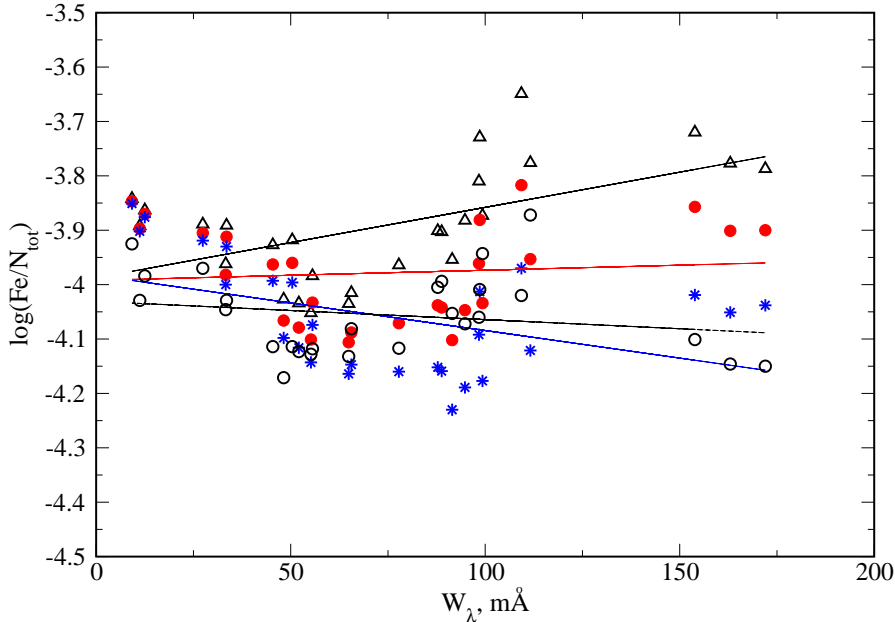


Figure 3: Iron abundance from individual lines versus equivalent width. The data obtained using the oscillator strengths from Raassen and Uylings (1998) for  $\xi_t = 1.4, 1.7$  and  $2.0 \text{ km c}^{-1}$ , are indicated by the open triangles, filled circles, and asterisks, respectively. The open circles correspond to the data obtained with  $\xi_t = 1.7 \text{ km c}^{-1}$  and the oscillator strengths from Melendez and Barbuy (2009). The straight lines indicate a linear fit.

## 5 The oxygen abundance in hot stars

The list of lines from which the oxygen abundance in the stars was determined is given in Table 4. The atomic data for the transitions, namely, wavelengths ( $\lambda$ ), oscillator strengths ( $\log gf$ ), lower-level excitation energies ( $E_{exc}$ ), radiative damping constants ( $\log \gamma_{rad}$ ), and quadratic Stark ( $\log \gamma_4$ ) and van der Waals ( $\log \gamma_6$ ) broadening constants per particle at  $T = 10^4 \text{ K}$  were taken from VALD (Kupka et al. 1999), except for the oscillator strength for the  $6300 \text{ Å}$  line



Table 2: Characteristics of the observations.

Star	HD	$\lambda/\Delta\lambda$	$S/N >$	Source
Sun		300000	300	Kurucz et al. (1984)
Procyon	61421	65000	200	Korn et al. (2003)
	32115	30000	150	Bikmaev et al. (2002)
Vega	172167	60000	200	A. Korn, private communication
Sirius	48915	70000	500	Furenlid et al. (1995)
Deneb	197345	42000	200	ELODIE <a href="http://atlas.obs-hp.fr/elodie/">http://atlas.obs-hp.fr/elodie/</a>

Table 3: Stellar parameters.

Star	HD	$T_{\text{eff}}$	$\log g$	[Fe/H]	$\xi_t$	$\log \varepsilon$	$\sigma$	Source
Sun		5777	4.44	0.0	0.9	8.74	0.03	
Procyon	61421	6590	4.00	0.0	1.8	8.73	0.03	Chiavassa et al. (2012)
	32115	7250	4.20	0.0	2.3	8.78	0.09	Fossati et al. (2011)
Vega	172167	9550	3.95	-0.5	2.0	8.59	0.01	Przybilla et al. (2000)
Sirius	48915	9850	4.30	0.4	1.8*	8.42	0.03	Hill and Landstreet (1993)
Deneb	197345	8525	1.10	-0.2	8.0	8.58	0.01	Schiller and Przybilla (2008)

\* Determined in this paper

calculated by Froese Fisher et al. (1998). For Vega, we performed our non-LTE calculations with the model atom from Przybilla et al. 2000 (P00) and updated one with data from Barklem 2007. The derived abundances are given in Table 5. We separated the lines into two groups: with small ( $\Delta_{non-LTE} \simeq -0.05$  dex) and large ( $\Delta_{non-LTE} \simeq -1$  dex) departures from LTE. Here, the non-LTE correction  $\Delta_{non-LTE} = \log \varepsilon_{non-LTE} - \log \varepsilon_{LTE}$ . In LTE, the abundance difference between the two groups is 1.23 dex. In our non-LTE calculations with P00 atom model, the difference decreases considerably and is 0.33 dex. With the new data, the situation changes for the better, but a difference of 0.14 dex still remains. The departures from LTE have increased, because decreasing of the rate coefficients for the most important transitions for statistical equilibrium (with  $C_{lu} \sim 10^7 \text{ cm}^{-3}$  or more). For example, for the  $3s \ ^5S^\circ - 3p \ ^5P$  transition, in which the 7771-5 Å lines are formed, the rate coefficient decreased by a factor of 1.4. Test calculations showed that such a change in the rate coefficient only for one transition makes the largest contribution to the change in the non-LTE correction for the 7771-5 Å lines. Przybilla et al. (2000) et al. (2000) estimated the accuracy of the atomic data to be 10 % for radiative transitions and 50 % for collisional ones. Therefore, we believe that the uncertainty of our non-LTE calculations for Vega is probably related only to the data for collisions with electrons. We decided to introduce a scaling factor for the rate coefficients from Barklem (2007), derived from the requirement, that different lines must give the same abundance. The obtained scaling factor  $S_{e-} = 0.25$ , the abundance difference 0.02 dex between the two groups of lines for Vega is achieved.

Thereafter, similar non-LTE calculations were performed for HD 32115 and Sirius; the results are presented in Tables 5 and 6. For HD 32115, the group of lines with large non-LTE corrections includes not only the 7771-5 Å lines but also the 8446 and 9266 Å lines. With the data from Barklem (2007), the difference between the abundances from different groups of lines is 0.09 and 0.14 dex for HD 32115 and Sirius, respectively, and reduces down to 0.04 and 0.02 dex when using a scaling factor  $S_{e-} = 0.25$ .

## 6 The solar oxygen abundance

The abundance was derived from visible (6300, 6158 Å) and IR (7771-5, 8446 Å) (see Fig. 4) O I lines (see Table 7). There is no agreement between the visible lines: in LTE the difference between the abundances obtained from the 6300 and 6158 Å lines is very large, 0.17 dex. In the non-LTE case, the difference reduces only slightly to 0.15 dex. We believe the abundance from the 6158 Å line to be reliable, because it is not blended and is much stronger than the forbidden line. There are several factors related to the 6300 Å line that could lead to this discrepancy. Figure 4 shows the profile of this line in the solar spectrum from the Atlas by Kurucz et al. (1984). The abundance derived from this line can not be referred to as reliable, because O I 6300.304 is weak and is blended with the Ni I 6300.336 Å line. In addition, there is an uncertainty in the oscillator strength: VALD and NIST give different values of  $\log gf = -9.82$  and  $-9.72$ . We use the latter value of  $\log gf = -9.72$  calculated theoretically by Froese Fisher et al. (1998). It should be noted that with the oscillator strength from VALD, the abundance difference between the 6300 and 6158 Å lines is much smaller, 0.05 dex. Here, we

Table 4: List of lines with atomic parameters.

$\lambda$ , Å	$E_{exc}$ , H,	$\log gf$	$\log \gamma_{rad}$	$\log \gamma_4$	$\log \gamma_6$	Transition
3947.29279	9.146	-2.096	6.660	-4.700	-7.957	$3s^5S^\circ - 4p^5P$
3947.48274	9.146	-2.244	6.660	-4.700	-7.957	$3s^5S^\circ - 4p^5P$
3947.58272	9.146	-2.467	6.660	-4.700	-7.957	$3s^5S^\circ - 4p^5P$
4368.19244	9.521	-2.665	8.760	-4.680	-7.946	$3s^3S^\circ - 4p^3P$
4368.24242	9.521	-1.964	8.760	-4.680	-7.946	$3s^3S^\circ - 4p^3P$
4368.26242	9.521	-2.186	8.760	-4.680	-7.946	$3s^3S^\circ - 4p^3P$
5330.72716	10.741	-2.415	7.550	-3.430	-	$3p^5P - 5d^5D^\circ$
5330.73716	10.741	-1.570	7.550	-3.430	-	$3p^5P - 5d^5D^\circ$
5330.73716	10.741	-0.984	7.550	-3.430	-	$3p^5P - 5d^5D^\circ$
6155.96637	10.741	-1.363	7.600	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6155.96637	10.741	-1.011	7.610	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6155.98637	10.741	-1.120	7.610	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6156.73616	10.741	-1.488	7.610	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6156.75616	10.741	-0.899	7.610	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6156.77615	10.741	-0.694	7.620	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6158.14579	10.741	-1.841	7.620	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6158.17578	10.741	-0.996	7.620	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6158.18577	10.741	-0.409	7.610	-3.960	-6.860	$3p^5P - 4d^5D^\circ$
6300.30400	0.000	-9.720*	-2.170	-	-	$2p^3P - 2p^1D$
7771.94130	9.146	0.369	7.520	-5.550	-7.469	$3s^5S^\circ - 3p^5P$
7774.16071	9.146	0.223	7.520	-5.550	-7.469	$3s^5S^\circ - 3p^5P$
7775.39037	9.146	0.001	7.520	-5.550	-7.469	$3s^5S^\circ - 3p^5P$
8446.24912	9.521	-0.463	8.770	-5.440	-	$3s^3S^\circ - 3p^3P$
8446.35909	9.521	0.236	8.770	-5.440	-	$3s^3S^\circ - 3p^3P$
8446.75898	9.521	0.014	8.770	-5.440	-	$3s^3S^\circ - 3p^3P$
9265.82735	10.741	-0.719	7.900	-4.950	-	$3p^5P - 3d^5D^\circ$
9265.92732	10.741	0.126	7.940	-4.950	-	$3p^5P - 3d^5D^\circ$
9266.00730	10.741	0.712	7.880	-4.950	-	$3p^5P - 3d^5D^\circ$

\* – The data from NIST

Table 5: Oxygen abundances for Vega and HD 32115.

$\lambda$ Å	$\log \varepsilon_{LTE}$	$\log \varepsilon_{non-LTE}$ P00	$\Delta_{non-LTE}$ P00	$\log \varepsilon_{non-LTE}$ B07	$\Delta_{non-LTE}$ B07	$\log \varepsilon_{non-LTE}$ 1/4(B07)	$\Delta_{non-LTE}$ 1/4(B07)
Vega							
5330	8.61	8.60	−0.01	8.59	−0.02	8.59	−0.02
6155	8.64	8.62	−0.02	8.61	−0.03	8.61	−0.03
6156	8.64	8.62	−0.02	8.60	−0.04	8.60	−0.04
6158	8.64	8.62	−0.02	8.60	−0.04	8.60	−0.04
Mean	8.63	8.62		8.60		8.60	
7771	9.84	8.96	−0.88	8.74	−1.09	8.58	−1.26
7774	9.83	8.94	−0.89	8.73	−1.10	8.57	−1.26
7775	9.80	8.95	−0.85	8.74	−1.05	8.59	−1.21
Mean	9.86	8.95		8.74		8.58	
HD 32115							
3947	8.77	8.76	−0.01	8.77	0.00	8.77	0.00
4368	8.77	8.77	−0.01	8.77	0.00	8.77	0.00
6155	8.76	8.74	−0.02	8.73	−0.03	8.73	−0.03
6158	8.83	8.80	−0.03	8.79	−0.04	8.79	−0.04
Mean	8.78	8.77		8.76		8.76	
7771	9.60	9.10	−0.50	8.96	−0.64	8.92	−0.68
7774	9.59	9.09	−0.50	8.93	−0.66	8.89	−0.70
7775	9.47	8.99	−0.48	8.94	−0.63	8.81	−0.66
8446	9.34	8.86	−0.48	8.73	−0.61	8.64	−0.70
9266	9.02	8.79	−0.23	8.71	−0.31	8.71	−0.30
Mean	9.40	8.97		8.85		8.80	

Table 6: Oxygen abundance for Sirius.

$\lambda$ Å	$\log \varepsilon_{LTE}$	$\log \varepsilon_{non-LTE}$ B07	$\Delta_{non-LTE}$ B07	$\log \varepsilon_{non-LTE}$ 1/4(B07)	$\Delta_{non-LTE}$ 1/4(B07)
5330	8.49	8.47	-0.02	8.47	-0.02
6155	8.44	8.42	-0.02	8.41	-0.03
6156	8.44	8.41	-0.03	8.41	-0.03
6158	8.44	8.42	-0.02	8.42	-0.02
Mean	8.45	8.43		8.43	
7771	9.46	8.62	-0.82	8.45	-1.01
7774	9.38	8.57	-0.78	8.41	-0.96
7775	9.21	8.53	-0.66	8.38	-0.83
Mean	9.35	8.57		8.41	

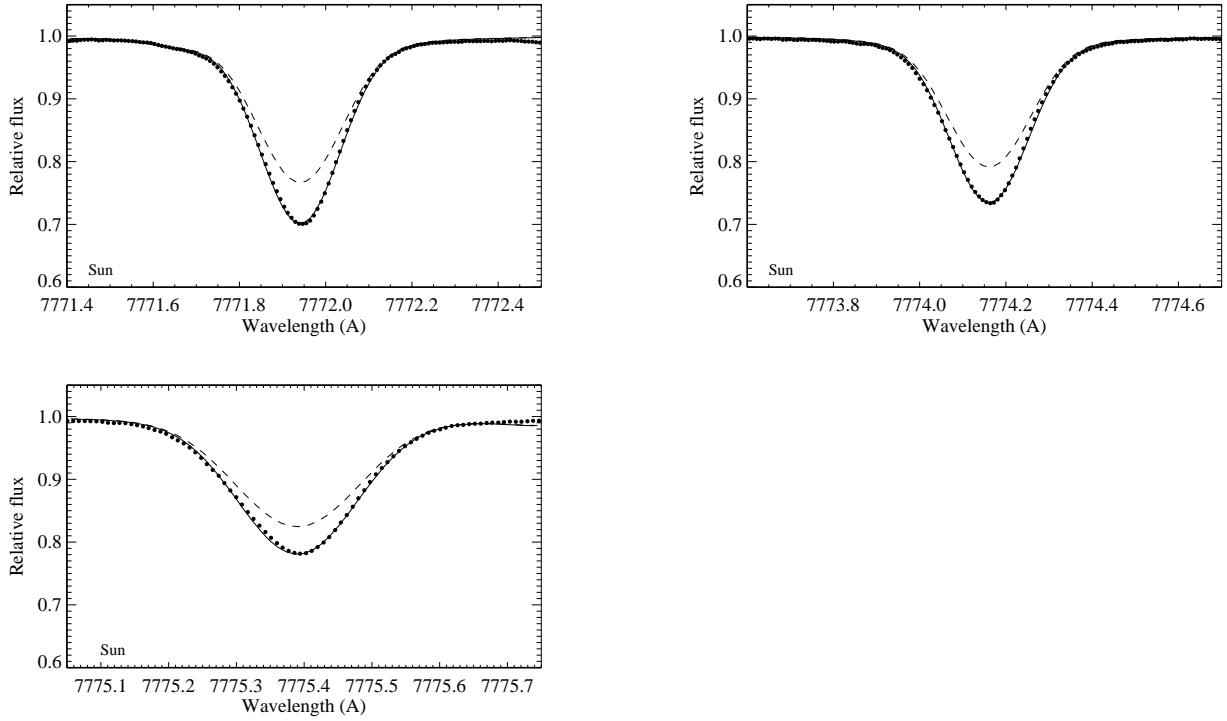


Figure 4: The O I IR lines in the solar spectrum. The circles, the dotted line, and the solid line indicate the observed spectrum, the synthetic lte-spectrum, and the non-LTE synthetic spectrum with the oxygen abundance  $\log \varepsilon = 8.75$  respectively.

use classical 1D model atmospheres, but the formation of these lines may be affected by 3D-effects. From Caffau et al. (2008) we took the 3D corrections that the authors recommend to add to the abundance derived with 1D model atmospheres. In this case, the difference between the abundances from visible lines reduces down to 0.05 dex.

In LTE the abundance from IR lines is higher than that from visible ones by 0.14 dex. In non-LTE, with H I collisions taken into account, this difference  $\Delta \log \varepsilon(IR - vis) = 0.04$  dex for the model atom by Przybilla et al. (2000) and completely vanishes for the updated model atom. If neglecting collisions with hydrogen atoms, the abundance from IR lines turns out to be, on average, even lower than that from weak lines. The differences are  $\Delta \log \varepsilon(IR - vis) = 0.05$  and 0.13 dex for the model atoms from Przybilla et al. (2000) and the updated one, respectively. We found that with updated model atom and with taking into account collisions with hydrogen atoms,  $\Delta \log \varepsilon(IR - vis) = 0$ , i.e., the abundance averaged separately over the IR and visible lines is the same,  $\log \varepsilon = 8.74 \pm 0.05$ . However, there is no agreement between the 6300 and 6158 Å lines in this case. If the 3D corrections are applied, then  $\Delta \log \varepsilon(IR - vis) = 0.02$ . In this case the abundance difference between the visible lines is reduced, and the rms error becomes smaller  $\log \varepsilon = 8.78 \pm 0.03$ .

Table 8 compares the abundances from individual lines with the results from Caffau et al. (2008) (C08). The C08(1D) column contains the LTE abundance derived by Caffau et al. (2008) with the 1D<sub>LHD</sub> model atmosphere. There is agreement between the abundances from different lines within 0.05 dex, except for the 6158 Å line for which the difference is 0.17 dex. A discrepancy is obtained from this line not only in our paper; the difference of the abundances from this line between the data from Caffau et al. (2008) and Asplund et al. (2004) is 0.13 dex. The two C08(HM) columns contain the non-LTE corrections calculated with the HM74 model atmosphere with and without allowance for the collisions with hydrogen atoms. The non-LTE corrections are in agreement within 0.05 dex; the difference is largest for the strongest 7771 Å line at  $S_H = 0$ , for which  $\Delta_{non-LTE} = -0.23$  dex. Table 9 compares the abundances from individual lines with the results from Asplund et al. (2004) (A04) obtained with the MARCS 1D model atmosphere. In the LTE and non-LTE cases, there is agreement within 0.04 dex for all lines except 6300 Å, for which the difference is 0.06 dex. When using the same solar spectrum, identical atomic data, and the same model atmosphere (HM74) in Asplund et al. (2004) and Caffau et al. (2008), the abundance from the forbidden line differs by 0.09 dex. This is most likely related to the placement of the continuum.

If the 3D corrections from Caffau et al. (2008) are added to the non-LTE abundance that we derived with the updated model, then the line-to-line scatter is 0.05 dex with  $S_H = 1$  and 0.9 dex with  $S_H = 0$ . Because of the uncertainties listed above, it cannot be concluded reliably for oxygen using only the solar spectrum that  $S_H = 1$ . Therefore, we performed similar calculations for Procyon (Table 10). Nobody has performed 3D calculations for O I lines in the spectrum of Procyon so far. But the temperature of Procyon is higher, the 3D corrections are probably smaller than those for the Sun. In Procyon, we again divided the lines into two groups, depending on the non-LTE correction. For weak visible lines,  $\Delta_{non-LTE}$  does not exceed 0.07 dex in absolute value; for IR lines,  $\Delta_{non-LTE} > 0.30$  dex. The abundances from the two groups of lines coincide at  $S_H = 1$ , and the difference between them is 0.13 dex at  $S_H = 0$ . For Procyon, we can unequivocally conclude that the collisions with hydrogen atoms with  $S_H = 1$

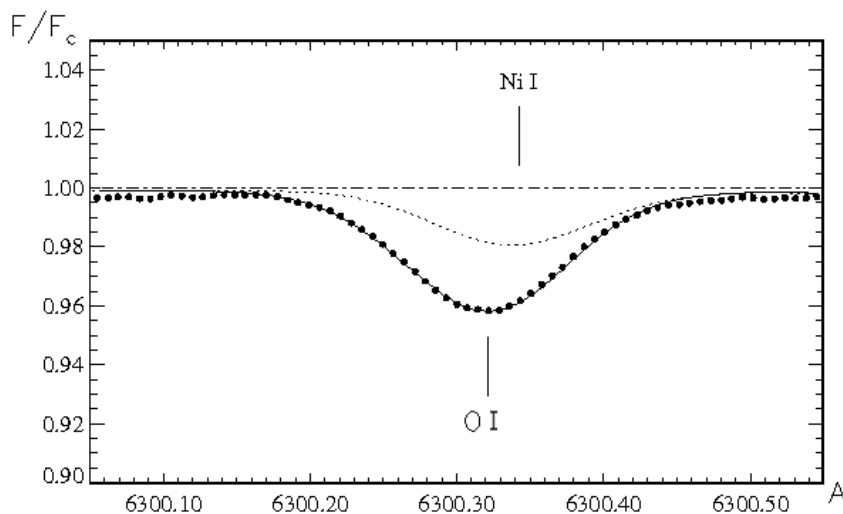


Figure 5: The [O I] 6300 Å line in the solar spectrum. The circles, the dotted line, and the solid line indicate the observed spectrum, the synthetic spectrum computed without oxygen, and the synthetic spectrum with the oxygen abundance  $\log \varepsilon = 8.67$  respectively.

should be taken into account.

For cool stars, where collisions with hydrogen atoms are more efficient, than collisions with electrons, scaling the transition rate coefficients under collisions with electrons does not virtually influence on non-LTE result. It is worth noting, that for the Sun, when moving from  $S_{e-} = 1$  to  $S_{e-} = 0.25$ , the non-LTE correction for the 7771 Å line changes only by 0.01 dex. For Procyon, the latter is 0.02 dex.

## 7 The non-LTE correction for model atmospheres with different parameters

We calculated the non-LTE corrections for O I lines for Kurucz’s classical model atmospheres with the following parameters:  $T_{\text{eff}} = 5000 - 10000$  K at 1000-K steps,  $\log g = 2$  (supergiants) and 4 (main-sequence stars), solar chemical composition, an oxygen abundance of 8.83, and microturbulence  $\xi_t = 2 \text{ km c}^{-1}$ . The parameter of collisions with hydrogen atoms is  $S_H = 1$ . The calculations were performed with the updated model atom with collision rate coefficients from Barklem (2007) and with rate coefficients reduced by a factor of 4. The non-LTE correction and equivalent width for the 7771 Å line are given in Table 11 and Fig. 6. The non-LTE corrections for the remaining lines of this multiplet are slightly smaller in absolute value and behave similarly. Here, the non-LTE correction should be understood as the difference between the non-LTE and LTE abundances corresponding to the non-LTE equivalent width. As expected, the departures from LTE are enhanced with increasing  $T_{\text{eff}}$  and decreasing  $\log g$ , reaching almost two orders of magnitude in some cases. The non-LTE corrections for lines with large departures

Table 7: Solar oxygen abundance.

$\lambda$ Å	LTE	non-LTE P00	$\Delta_{non-LTE}$ P00	non-LTE B07	$\Delta_{non-LTE}$ B07	non-LTE + 3D	non-LTE P00	$\Delta_{non-LTE}$ P00	non-LTE B07	$\Delta_{non-LTE}$ B07
$S_H=1$						$S_H=0$				
6300	8.67	8.67	0.00	8.67	0.00	8.72	8.67	0.00	8.67	0.00
6158	8.84	8.82	-0.02	8.82	-0.02	8.79	8.81	-0.03	8.79	-0.05
7771	8.92	8.78	-0.14	8.74	-0.18	8.80	8.69	-0.23	8.58	-0.34
7774	8.91	8.78	-0.13	8.75	-0.16	8.79	8.70	-0.21	8.59	-0.32
7775	8.89	8.78	-0.11	8.75	-0.14	8.78	8.71	-0.18	8.61	-0.28
8446	8.86	8.76	-0.10	8.74	-0.12	8.77	8.67	-0.19	8.61	-0.25

Table 8: Comparison of our results with those from Caffau et al. (2008)

$\lambda$ Å	$\log \varepsilon$ LTE	$\log \varepsilon$ LTE C08(1D)	$\Delta_{non-LTE}$ $S_H=1$	$\Delta_{non-LTE}$ $S_H=1$ C08(HM)	$\Delta_{non-LTE}$ $S_H=0$	$\Delta_{non-LTE}$ $S_H=0$ C08(HM)
6300	8.67	8.64	0.00	0.00	0.00	0.00
6158	8.84	8.67	-0.02	0.00	-0.03	0.00
7771	8.92	8.97	-0.14	-0.16	-0.23	-0.28
7774	8.91	8.94	-0.13	-0.14	-0.21	-0.25
7775	8.89	8.92	-0.11	-0.12	-0.18	-0.21
8446	8.86	8.80	-0.10	-0.08	-0.19	-0.15

Table 9: Comparison of our results with those from Asplund et al. (2004) obtained with the MARCS 1D model atmosphere.

$\lambda$ Å	LTE	LTE A04	non-LTE	$\Delta_{non-LTE}$	non-LTE A04	$\Delta_{non-LTE}$ A04
6300	8.67	8.73	8.67	0.00	8.73	0.00
6158	8.84	8.80	8.81	-0.03	8.77	-0.03
7771	8.92	8.95	8.69	-0.23	8.71	-0.24
7774	8.91	8.94	8.70	-0.21	8.71	-0.23
7775	8.89	8.91	8.71	-0.18	8.71	-0.20
8446	8.86	8.88	8.67	-0.19	8.67	-0.21



Table 10: Oxygen abundance for Procyon.

$\lambda$ Å	$\log \varepsilon_{LTE}$	$\log \varepsilon_{non-LTE}$ $S_H = 1$	$\Delta_{non-LTE}$ $S_H = 1$	$\log \varepsilon_{non-LTE}$ $S_H = 0$	$\Delta_{non-LTE}$ $S_H = 0$
6155	8.80	8.76	-0.04	8.74	-0.06
6156	8.72	8.69	-0.03	8.67	-0.05
6158	8.79	8.74	-0.05	8.72	-0.07
Mean	8.77	8.73		8.71	
7771	9.28	8.76	-0.52	8.59	-0.69
7774	9.26	8.76	-0.50	8.59	-0.67
7775	9.18	8.73	-0.45	8.57	-0.61
8446	9.00	8.70	-0.30	8.58	-0.42
8446	9.04	8.71	-0.33	8.58	-0.46
Mean	9.15	8.73		8.58	

from LTE are very sensitive to changes in temperature, surface gravity, and equivalent width (oxygen abundance). We stress that the calculated non-LTE correction can be used to derive the non-LTE abundance if not only the stellar parameters but also the line equivalent widths are close to the values from Table 11. Whereas the non-LTE corrections for visible lines in the atmospheres of main-sequence stars are small ( $< -0.05$  dex), they cannot be neglected for supergiants (Table 11). For example,  $\Delta_{non-LTE} = -0.12$  dex for the 6158 Å line at  $T_{\text{eff}} = 7000$  K. In the atmospheres of supergiants, reducing the electron collision rate coefficients by a factor of 4 affects weakly the SE of O I, because collisions are ineffective. The different case is in the  $\log g = 4$  models with  $T_{\text{eff}} > 7000$  K. Therefore, the curves in Fig. 6 diverge at  $T_{\text{eff}} \simeq 7000$  K.

To check our non-LTE method for supergiants, we determine the oxygen abundance for Deneb (Table 12). We do not use the IR lines, because they are very strong; the observed equivalent width for the 7771 Å line is 550 mÅ (Takeda 1992). The mean LTE and non-LTE abundances from three O I lines are  $\log \varepsilon = 8.76 \pm 0.03$  and  $\log \varepsilon = 8.57 \pm 0.01$ , respectively. For comparison, Schiller and Przybilla (2008) obtained similar values,  $\log \varepsilon_{LTE} = 8.80 \pm 0.07$  and  $\log \varepsilon_{non-LTE} = 8.62 \pm 0.02$ . The small difference in abundance between this study and Schiller and Przybilla (2008) is most likely because of using a different set of lines.

## 8 Conclusions

We performed non-LTE calculations for O I with electron collisional data from Barklem (2007) and determined the oxygen abundance for six stars. A significant progress was achieved in reducing the difference between the abundances derived from IR and visible lines. It amounts to  $\Delta \log \varepsilon(\text{IR} - \text{vis}) = 0.09, 0.14, \text{ and } 0.14$  dex for HD32115, Vega, and Sirius, respectively. For comparison,  $\Delta \log \varepsilon(\text{IR} - \text{vis}) = 0.33$  dex for Vega when using the model atom

Table 11: Non-LTE corrections for the O I 7771 Å and 6158 Å lines for a grid of model atmospheres. The equivalent width in mÅ is given in parentheses.

$T_{eff}, K$	7771 Å				6158 Å
	log g = 4		log g = 2		B07, 1/4(B07)
	B07	1/4(B07)	B07	1/4(B07)	
10000	-1.07 (246)	-1.26 (272)	-1.87 (291)	-1.96 (302)	-0.26 (103)
9000	-0.95 (260)	-1.10 (281)	-1.64 (301)	-1.70 (311)	-0.18 (120)
8000	-0.81 (261)	-0.90 (275)	-1.40 (310)	-1.46 (318)	-0.13 (127)
7000	-0.65 (221)	-0.69 (226)	-1.28 (296)	-1.31 (301)	-0.12 ( 98)
6000	-0.34 (133)	-0.36 (135)	-1.07 (233)	-1.09 (235)	-0.08 ( 41)
5000	-0.10 ( 38)	-0.10 ( 38)	-0.49 (100)	-0.50 (101)	-0.05 ( 8)

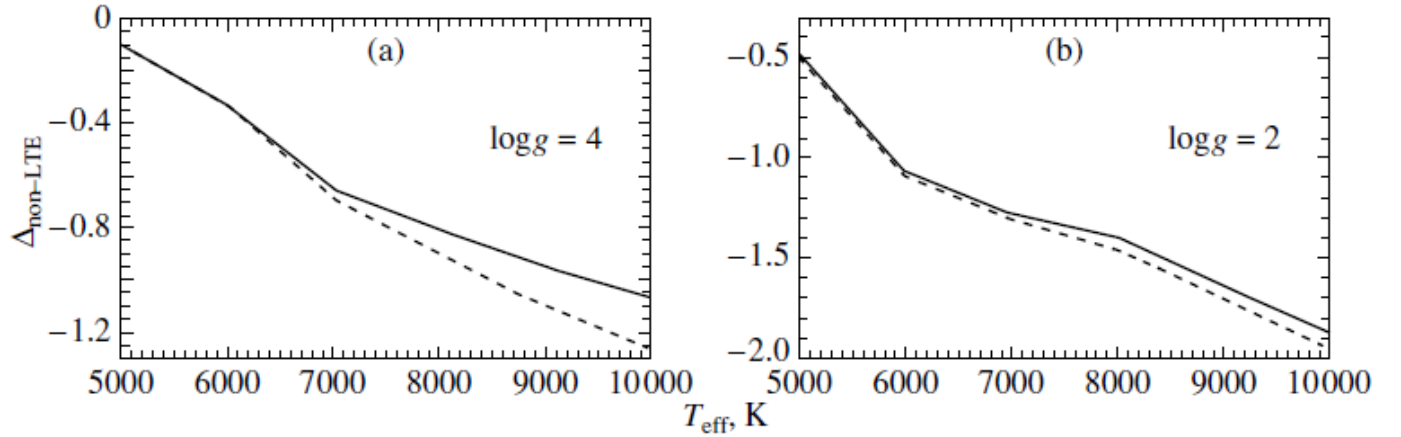


Figure 6: Non-LTE correction for the 7771 Å line versus  $T_{eff}$  for (a) main-sequence stars and (b) supergiants. The solid and dashed lines represent the calculations with the original data from Barklem (2007) and with the rate coefficients reduced by a factor of 4, respectively.

Table 12: Oxygen abundance for Deneb.

$\lambda, \text{Å}$	EW, m Å	$\log \varepsilon_{LTE}$	$\log \varepsilon_{non-LTE}$	$\Delta_{non-LTE}$
5330	31.4	8.73	8.58	-0.15
6155-6	117.1	8.76	8.57	-0.19
6158	92.9	8.79	8.59	-0.20
Mean		8.76	8.57	

from Przybilla (2000). To reconcile the abundances from different lines in Vega, we introduced a scaling factor  $S_{e-} = 0.25$  to the rate coefficients for collisions with electrons. This value is appropriate for other two A-type stars. The mean abundances, deduced from the visible and IR lines are  $\log \varepsilon = 8.78 \pm 0.09$ ,  $8.59 \pm 0.01$ , and  $8.42 \pm 0.03$  for HD 32115, Vega, and Sirius, respectively.

For cool stars (the Sun and Procyon), for which the main uncertainty of the non-LTE calculations is associated with allowance for the hydrogen collisions, we showed that the scatter of the abundances from different lines is minimal when applying the Drawin's formalism in invariable form ( $S_H = 1$ ). The solar oxygen abundance is  $\log \varepsilon = 8.74 \pm 0.05$  in this case and  $\log \varepsilon_{+3D} = 8.78 \pm 0.03$  when the 3D corrections from Caffau et al. (2008) are applied. Scaling the rate of collisions with electrons affects weakly the abundance; the non-LTE correction changes by no more than 0.02 dex. The statistical error in the abundance determined from solar O I lines is only 0.03 dex, less than that in Asplund et al. (2009). However, a conservative estimate of the error should take into account the change in abundance due to the use of different observational data ( $\sigma = 0.01$ ), different continuum placement ( $\sigma = 0.08$ ), different model atmospheres ( $\sigma = 0.06$ ), and different atomic data ( $\sigma = 0.02$ ). We estimate the total error to be 0.11 dex. Note that the solar oxygen abundance we derived is 0.02 dex higher than that recommended by Caffau et al. (2008) and 0.09 dex exceeds the value from Asplund et al. (2009). Nevertheless, it is lower (by 0.08 dex) than that needed to reconcile the theoretical and observed density and sound speed profiles. Recent modeling by Antia and Basu (2011) showed that not only the oxygen abundance but also the abundances of heavy elements, such as Ne, are important to achieve agreement between the theory and observations. The difference between the theory and observations is minimized with the chemical composition of the solar atmosphere that is given by Caffau et al. (2011) if the neon abundance is increased by a factor of 1.4.

We calculated the non-LTE corrections for the O I 7771 Å and 6158 Å lines for a grid of model atmospheres with  $T_{\text{eff}} = 5000 - 10000$  K,  $\log g = 2$  and 4, solar chemical composition, an oxygen abundance of 8.83, and microturbulence  $\xi_t = 2 \text{ km c}^{-1}$ . For IR lines in the atmospheres of supergiants,  $\Delta_{\text{non-LTE}}$  reaches almost two orders of magnitude. The non-LTE corrections for visible lines in supergiants reach 0.27 dex in absolute value, as distinct from main-sequence stars in which the non-LTE corrections for these lines do not exceed 0.05 dex. The calculated corrections can be applied to determine the non-LTE abundances if not only the atmospheric parameters but also the line equivalent widths are close to the tabulated ones.

## 9 Acknowledgments

We wish to thank D. Shulyak, who computed the model atmospheres of Vega and HD 32115, and Yu. Pakhomov for the model atmosphere of Deneb. We used the DETAIL code provided by K. Butler, a participant of the "Non-LTE Line Formation for Trace Elements in Stellar Atmospheres" School (July 29-August 2, 2007, Nice, France). T.M. Sitnova and L.I. Mashonkina are grateful to the Swiss National Science Foundation (the SCOPES project, IZ73Z0-128180/1) for partial financial support of our study. The work is supported by a grant on Leading Scientific

Schools 3602.2012.2 and by Federal agency of science and innovations (2012-1.5-12-000-1011-014/8529).

## References

- [1] C. Abia, R. Rebolo, *Astrophys. J.*, Part 1, **347**, 186 (1989);
- [2] C. Allende Prieto, M. Asplund, P. Fabiani Bendicho, *Astron. Astrophys.*, **423**, 1109 (2004);
- [3] E. Anders and N. Grevesse, *Geochimica et Cosmochimica Acta*, vol. 53, 197, (1989);
- [4] H. M. Antia and Sarbani Basu, *J. Phys.: Conf. Ser. Vol. 271*, 012034 (2011);
- [5] M. Asplund, N. Grevesse, A. J. Sauval et al., *Astron. Astrophys.*, **417**, 751 (2004);
- [6] M. Asplund, N. Grevesse, A. J. Sauval, P. Scott), *Astron. Astrophys.*, **481**, 522 (2009);
- [7] John N. Bahcall and Aldo M. Serenelli, *Astrophys. J.*, **626**, 530 (2005);
- [8] P. S. Barklem, *Astron. Astrophys.*, **462**, 781 (2007);
- [9] P. S. Barklem, A. K. Belyaev, A. S. Dickinson, F. X. Gadea, *Astron. Astrophys.*, **519**, A20 (2010);
- [10] P. S. Barklem, A. K. Belyaev, A. Spielfiedel et al., *Astron. Astrophys.*, **541**, A80 (2012);
- [11] K. Butler, J. Giddings, *Newsletter on Analysis of Astronomical Spectra 9*, University of London, **723**, (1985);
- [12] A. K. Belyaev, & P. Barklem, *Phys.Rev.*, A68, 062703, ( 2003)
- [13] A. K. Belyaev, P. S. Barklem, A. S. Dickinson, & F. X. Gadéa, *Phys. Rev. A*, 81, 032706, (2010)
- [14] A. K. Belyaev, J. Grosser, J. Hahne, & T. Menzel, *Phys.Rev.*, A60, 2151, (1999)
- [15] I. F. Bikmaev, T. A. Ryabchikova, H. Bruntt et al., *Astron. Astrophys.*, **389**, 537 (2002);
- [16] A.K. Bhatia, S.O. Kastner *Astrophys. J.*, 96, 325 (1995);
- [17] M. Carlsson and P. G. Judge, *Astrophys. J.*, **402**, 344 (1993);
- [18] E. Caffau, H. G. Ludwig, M. Steffen et al., *Astron. Astrophys.*, **488**, I3, 1031 (2008);
- [19] E. Caffau, H. G. Ludwig, M. Steffen et al., *Solar Physics*, V268, I2, 255, (2011);
- [20] A. Chiavassa, L. Bigot, P. Kervella et al., *Astron. Astrophys.*, **540**, id.A5 (2012);
- [21] H.W. Drawin, *Z. Physik*, **211**, 404 (1968);

- [22] H.W. Drawin, Z. Physik, **225**, 483 (1969);
- [23] D. Fabbian, M. Asplund, P. S. Barklem et al., Astron. Astrophys., **500**, 1221 (2009);
- [24] L. Fossati, T. Ryabchikova, D. V. Shulyak et al., Monthly Notices of the Royal Astronomical Society, **417**, 495 (2011);
- [25] Froese Fisher and M. Saparov, G. Gaigalas, M. Godefroid, Atomic data and nuclear data tables, **70**, 119 (1998);
- [26] I. Furenlid, T. Westin, R. L. Kurucz, Workshop on Laboratory and astronomical high resolution spectra. San Francisco: Astronomical Society of the Pacific (ASP); c1995; edited by A.J. Sauval, R. Blomme, and N. Grevesse, p.615;
- [27] F. Grupp, R. L. Kurucz, K. Tan, Astron. Astrophys., **503**, 177 (2009);
- [28] B. Gustafsson, B. Edvardsson, K. Eriksson et al., Astron. Astrophys., **486**, 951 (2008);
- [29] G.M. Hill, J.D. Landstreet, Astron. Astrophys., **276**, 142 (1993);
- [30] H. Holweger, E.A. Mueller, Solar Physics, **39**, 19 (1974);
- [31] A. Hui-Bon-Hoa, C. Burkhart, G. Alecian, Astron. Astrophys., **323**, 901 (1997);
- [32] H.R. Johnson, R.W. Milkey, L.W. Ramsey, Astrophys. J., **187**, 147 (1974);
- [33] Dan Kiselman, Astron. Astrophys., **245**, L9 (1991);
- [34] K. Kodaira and K. Tanaka, Astron. Soc. Japan 24, 355 (1972);
- [35] A. J. Korn, J. Shi, and T. Gehren, Astron. Astrophys., **407**, 691 (2003);
- [36] O. Kochukhov et. al. Spectrum synthesis for magnetic, chemically stratified stellar atmospheres, in Magnetic Stars 2006, eds I. I. Romanyuk, D. O. Kudryavtsev, O. M. Neizvestnaya, V. M. Shapoval, 109, 118 (2007);
- [37] F. Kupka, N.E. Piskunov, T.A. Ryabchikova et al., Astron. Astrophys. Suppl., **138**, 119 (1999);
- [38] R. Kurucz, I. Furenlid, J. Brault, L. Testerman, National Solar Observatory Atlas, Sunspot, New Mexico: National Solar Observatory (1984);
- [39] R. Kurucz, Kurucz CD-ROM No. 13.(Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1993), **13**
- [40] J. D. Landstreet, Astron. Astrophys., **528**, A132 (2011);
- [41] M. Lemke, Astron. Astrophys., **240**, 331 (1990);
- [42] L. Mashonkina, A. J. Korn, N. Przybilla, Astron. Astrophys., **461**, 261 (2007);

- [43] L. Mashonkina, T. Gehren, J.R. Shi et al., *Astron. Astrophys.*, **528**, A87 (2011);
- [44] J. Meléndez, B. Barbuy, *Astron. Astrophys.* **497**, 611 (2009).
- [45] T. V. Mishenina, S. A. Korotin, V. G. Klochkova and V. E. Panchuk, *Astron. Astrophys.*, **353**, 978 (2000);
- [46] P. E. Nissen, F. Primas, M. Asplund and D. L. Lambert, *Astron. Astrophys.*, **390**, 235 (2002);
- [47] E. Nordlund, B. Plez, *Astron. Astrophys.*, **486**, 951 (2008);
- [48] E. Paunzen, I. Kamp, I. Kh. Iliev et al., *Astron. Astrophys.*, **345**, 597 (1999);
- [49] T. M. D. Pereira, M. Asplund, D. Kiselman., *Astron. Astrophys.*, **508**, 1403 (2009);
- [50] M. H. Pinsonneault and Franck Delahaye, *Astrophys. J.*, **649**, 529 (2006);
- [51] M. H. Pinsonneault and Franck Delahaye, *Astrophys. J.*, **704**, 1174 (2009);
- [52] N. Przybilla, K. Butler, S. R. Becker et al., *Astron. Astrophys.*, **359**, 1085 (2000);
- [53] H. M. Qiu, G. Zhao, Y. Q. Chen, Z. W. Li, *Astrophys. J.*, **548**, 953 (2001);
- [54] A. J. J. Raassen, P.H.M. Uylings, *Astron. Astrophys.* , **340**, 300 (1998);
- [55] Johannes Reetz, *Astrophysycs and Space Sience.* , **265**, 171 (1999);
- [56] N. A. Sakhibullin, *Tr. Kazan. Gor. Observ.*, **48**, 9 (1983);
- [57] C. Sneden, D. L. Lambert, R. W. Whitaker, *Astrophys. J.*, Part 1, **234**, 964 (1979);
- [58] W. Steenbock, H. Holweger, *Astron. Astrophys.* , **130**, 319 (1984);
- [59] F. Schiller and N. Przybilla, *Astron. Astrophys.*, **479**, 849 (2008);
- [60] D. Shulyak, V. Tsymbal, T. Ryabchikova, Ch. Stutz, W. W. Weiss, *Astron. Astrophys.*, **428**, 993 ( 2004);
- [61] N.G. Shchukina, *Kinem. Fiz. Nebes. Tel* (ISSN 0233-7665), **3**, 36 (1987).
- [62] Yoichi Takeda, *Astronomical Society of Japan* **44**, 3, 309 (1992);
- [63] Yoichi Takeda, *Astronomical Society of Japan* **47**, 463 (1995);
- [64] Henry van Regemorter, *Astrophys. J.*, **136**, 906 (1962);
- [65] R. Wooley, C. W. Allen, *Monthly Notices of the Royal Astronomical Society*, **108**, 292 (1948);